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Migration pathways of corn earworm (Lepidoptera: Noctuidae) indicated by tetroon trajectories

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Abstract

The corn earworm moth, *Helicoverpa zea* (Lepidoptera: Noctuidae), is a nocturnal pest insect that is capable of long-distance flights. Buoyant superpressure balloons (tetroons) with attached transponders were tracked as surrogate markers of moths migrating from three corn-growing regions in Texas. Launches were synchronized with peak emergence of corn earworm moths in June and July 1992. The tetroons were launched at the time (approximately 0.5 h after sunset) of peak take off (ascent of moths into the boundary layer) from the corn-growing areas, and ballasted to drift near the altitude (500–1000 m a.g.l.) of the maximum insect flight concentration. Each tetroon was followed by a tracking vehicle or the Argos satellite for maximum distances of 466 km per 9 h night flight, and for one to four successive nights. The endpoints of four of the six tetroons that were tracked for 9 h from Weslaco, Texas were clustered within a 40 km radius circle centered 35 km east of Uvalde, Texas. The prorated (9 h) vector-average of National Weather Service forecast trajectories at the surface and 85.0 kPa geopotential-height estimated mean atmospheric displacements 57% as long as, and 3° clockwise from seven observed 9 h tracks of tetroons. Implications of these findings are discussed relative to the prediction of insect migrations and development of area-wide pest management.

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1. Introduction

The corn earworm moth, *Helicoverpa zea* (Boddie) (Lepidoptera: Noctuidae), is a highly mobile pest insect that causes widespread economic damage to a variety of crops in the US including corn, cotton, soybean, tobacco and vegetables. Up to seven billion corn earworm are produced per spring generation in extreme northeastern Mexico and south-central Texas (Raulston et al., 1992). Long-distance migration of the corn earworm has often been cited as a major reason for ineffective control of the pest. Knowledge of the impact of migrant corn earworm on local populations has been noted as a key element of area-wide pest control programs (Knipling, 1955; 1979).

Convincing evidence supports hypotheses of long-distance flight of the corn earworm. Hartstack et al. (1982) found that first capture of adult corn earworm at College Station, Texas and Portland, Arkansas occurred 19 days and 33 days, respectively, before local diapause emergence in 1981, during which time there were excellent opportunities for atmospheric transport from Mexico. Raulston et al. (1990) found that adult emergence of corn earworm from pupae produced from larvae developing on fruiting corn in the Lower Rio Grande Valley (LRGV) did not result in a large trap peak and suggested that a large portion of the population emigrated. Wolf et al. (1990) monitored the flight of corn earworm adults for 400 km from their origin in the LRGV to San Antonio, Texas in 7.7 h using an airborne radar; maximum oviposition occurred three days later in cotton growing areas near Uvalde, Texas, 125 km west of San Antonio. Corn earworm moths have been captured that were contaminated with pollen exotic to the capture area (Hendrix et al., 1987; Lingren et al., 1993, 1994). Early spring captures of pollen-marked moths have often suggested displacements of more than 700 km from the nearest source areas.

Circadian and generation emergence cycles of corn earworm adults from fruiting corn are well established (Hayes, 1988; Lingren et al., 1988; Raulston et al., 1992). Emergence patterns from areas involved in the scope of this study have been established (Lopez et al., 1994; Raulston et al., 1994). Likewise, plumes of newly emergent corn earworm adults exiting corn fields have been studied in detail by visual observation using night vision equipment (P.D. Lingren, unpublished data, 1990) and radar (Wolf et al., 1990, 1994). These studies have shown a mean ascent rate of 3.2 m s^{-1} during the first 100 m above ground level (a.g.l.) with a decreased rate of about 2.0 m s^{-1} up to a mean flight altitude of 404 $\pm$ 119 m a.g.l.

Wind velocity below 1500 m altitude in the south-central US (Bonner, 1968) typically exceeds the corn earworm moth flight velocity measured by radar (W.W. Wolf, unpublished data, 1990), but wind velocity measurements have been inadequate for nocturnal insect flight studies. The National Weather Service (NWS) collects boundary layer wind data twice daily (07:00 h and 19:00 h Central Daylight Savings Time (CDST)) from a network of observing stations located 400 km apart. All time designations are CDST unless specified otherwise. Simulations from various diagnostic trajectory models using vertical wind profile data often show significant discrepancies from measured atmospheric trajectories (Crawford et al., 1982; Clarke et al., 1983). To improve the spatiotemporal representativeness of the wind velocity measurements, ascending pilot balloons (pibals) have been deployed to measure vertical profiles of nocturnal wind velocity near sites of insect emergence (Wolf et al., 1986). However, these measurements can not accurately describe wind velocity along the trajectory of dispersing noctuids.

W. W. Wolf (unpublished data, 1990) detected an over-flight of insects (a 280% increase from 21:40 h to 22:30 h) with a scanning radar near La Gloria, Texas on 6 June 1990. The site was 80 km downwind of a source of emerging corn earworm moths near Donna, Texas. The maximum airborne insect concentration at La Gloria occurred about 1 h after that observed at Donna. Moths flying from the source area near Donna would have required a displacement velocity of 22 m s^{-1} to travel from Donna to La Gloria. Moths flying downwind at 5 m s^{-1} would have required a wind speed of 17 m s^{-1} to achieve this displacement. Measurements at La Gloria on 6 June 1990 using the scanning radar and pibals documented wind speed values from 16 to 18 m s^{-1} at 800–1000 m altitude where the maximum moth concentration was noted from 22:30 h on 6 June 1990 to 00:31 h on 7 June 1990 (2.2–4.2 h after sunset). These data suggest that the insects were flying downwind at 5 m s^{-1}.

Mylar tetrahedral balloons (tetroons) have been used to study atmospheric transport of passive material such as airborne gases and particulates. Tetroons maintain a constant volume and, therefore, drift passively at altitudes of constant air density. A layer of constant air density is approximately horizontal in stable air over level terrain during typical nocturnal conditions. Tetroons have been deployed as tracers for numerous atmospheric studies, frequently for transport distances less than 100 km (Angell and Pack, 1962; Thomas and Vogt, 1990) owing to range limitations of the ground-based tracking radars. Paterson (1966) used return tag information to extend the documented range of tetroon trajectories to several hundred miles. Ground-based radars simultaneously tracked sets of three tetroons to derive relative diffusion coefficients (Angell et al., 1975), and coordinate moving (Lagrangian) measurements of atmospheric variables including air pollutant concentrations (Angell et al., 1972). Clawson et al. (1986) developed a LORAN-C (Long Range Aid to Navigation) transponder for tetroons that could be tracked for an unlimited range by a vehicle with an installed radio receiver. Unfortunately, few nocturnal boundary layer measurements have been performed with tetroons.

We used tetroons as surrogate markers of long-distance transport of corn earworm moths from source areas in the south-central US. Tetroons were launched nightly at the time of flight as noted by ground-based radar measurements and during the period of peak emergence as confirmed by moth emergence profiles from the area. Tetroons were deployed to attain an equilibrium altitude near that of the maximum insect flight concentration. This paper addresses the following objectives:

(1) to document the distance and direction of one-night tetroon trajectories as surrogates of corn earworm moths flying from source areas in northeastern Mexico and southern Texas;

(2) to document the distance and displacement of successive-night tetroon trajectories as surrogates of corn earworm moths flying from a source area in southeastern Texas.

2. Methods

2.1. Insect emergence

Two separate field studies were conducted synchronously with local peak emergence of corn earworm from corn in June and July 1992. Corn earworm pupae were excavated from 100 corn fields in the LRGV, 40 fields at Uvalde, Texas and 40 fields at Wharton, Texas to obtain a density and emergence profile for the respective areas. Following excavation, individual pupae were placed in small emergence tubes and placed in the soil following the methods of Raulston et al. (1992). The tubes were checked daily for adult emergence and emergence profiles were established to allow for release of tetroons at or near the time of peak adult emergence from corn at each study site.

2.2. Entomological radars

The initial field campaign was conducted in the LRGV. Two ground-based X-band (3.2 cm) radars (one scanning and one vertical-pointing) were used to document the orientation, flight speed, and aerial concentration of insects. The scanning radar (GBR1) was located about 15 km south-southwest of Weslaco, Texas to measure corn earworm moth migration near the prevailing downwind perimeter of the concentrated insect source area centered near Rio Bravo, Tamaulipas, Mexico. A vertical-pointing radar (VPR) operated 10 km south of McCook and 55 km downwind of GBR1 to continuously record moth over-flights.

2.3. Tetroons

Tetroons of 1 m^3 and 2 m^3 (Raven Industries, Inc., Sioux Falls, SD) made of transparent red mylar of 2 mil thickness inflated with helium gas were used for tracking. Aluminum foil patches (30 cm × 30 cm) were attached to three sides of the tetroon, excluding the top, to increase radar reflectivity. A 1.5-VDC strobe light (Northern, Burnsville, MN; model 16884-E) was attached to the base of the tetroon when sufficient lift was available for increased visibility of the tetroon location. A small electronic alarm clock was wired to a transistor and a 9-VDC alkaline battery to power a detonator attached to the side of the tetroon. The alarm clock was set to activate the detonator at 0.5 h before sunrise. The detonator, a model rocket engine igniter with 2 g of gun powder, burned a small hole in the tetroon which allowed helium to escape, and forced the tetroon to the ground.

Vertical atmospheric measurements of barometric pressure, air temperature, and wet bulb temperature were required to calculate air density values at the surface and at a predetermined altitude where the tetroon would drift (equilibrium level). A 403.5 MHz Airsonde (A.I.R., Boulder, CO; model AS-1C-PTH) attached to a pibal was launched, then tracked by an A.I.R. optical encoding theodolite. Data from the Airsonde were transmitted to an A.I.R. model AIR-3A Automated Data Acquisition System (ADAS) receiver. The data were sent to a laptop computer where they were concurrently saved on floppy disk and printed. We chose equilibrium levels within the nocturnal boundary layer that were high enough to ensure that the tetroon would not impinge on higher terrain and that the radio signal would be received at distances up to 30 km throughout the 9 h trajectory. The air density near the surface and at the equilibrium level were computed on a calculator. The difference between the air density values was used to determine the amount of lift needed for the tetroon to reach equilibrium.

2.4. Vehicle tracking of tetroons

An A.I.R. IS-4C-MET Cross-chain Loran Atmospheric Sounding System (CLASS) (subsequently referred to as the CLASS System) was used to measure atmospheric properties along the tetroon trajectories. The CLASS System consists of a digital radiosonde (A.I.R. model IS-4A-403L Intellisonde), an ANI-7000 (403 MHz) radio receiver, steerable directional antenna, an automatic Loran-C Navigation Aids (NAVAID) signal processor, and a PC-based processing system. The PC-based processing system is comprised of an HP Vectra QS/20 with a 40 MB hard disk, VGA card and monitor, 80387 numeric coprocessor, 8 MB RAM, and an A.I.R. model IS-4A-MDC METDECODER board. The CLASS System obtains 10 s averages of barometric pressure, air temperature, and relative humidity, and 60 s smoothed wind velocity values.

Modifications were made to the CLASS software and Intellisondes to allow for all-night balloon tracking. Data array sizes in the software were increased to extend the maximum time of data acquisition from 2 to 9 hours (approximately spanning the time from dusk until dawn for our observations). This was the maximum duration attainable due to HTBASIC programming language limitations. Initially, the two 9-VDC alkaline batteries inside the Intellisonde were supplemented with four external 9-VDC batteries. However, owing to weight constraints, 6-VDC lithium batteries were subsequently substituted and reduced the balloon payload by 49 g. Three of the 6-VDC lithium batteries were connected in series to supply 18 VDC, and connected in parallel with the internal batteries. The three 6-VDC lithium batteries were rated at 1300 ma h, enough power to run the Intellisonde for approximately 10 h.

The system operator monitored the position, speed, drift direction and altitude of the tetroon, as well as the ambient barometric pressure, air temperature, and relative humidity measured by the Intellisonde. The azimuthal direction of the tetroon relative to the tracking van was determined by manually rotating the antenna until a maximum radio signal was received from the Intellisonde. This was particularly important when the Loran navigation signals were not locked in, but meteorological data was still being received.

The driver of the tracking van and the radar operators communicated information regarding insect flight, wind velocity and tetroon location via mobile radio transceivers, cellular telephones and aircraft radios. The operator of GBR1 reported the time and altitude of peak moth exodus. This information was used nightly to properly ballast and synchronize the release of tetroons. The CLASS operator reviewed and adjusted system performance, and communicated tetroon trajectory coordinates and velocity to the driver. The driver of the tracking van recorded significant events along the balloon track including distance, location checkpoints, and time-marks on audio cassette tape, and communicated the location and velocity of the drifting tetroon to the radar operators. The driver also reviewed the locations of the vehicle and tetroon to determine which roads would maximize the reception range of the Intellisonde.

2.5. Satellite tracking of tetroons

For satellite tracking, a Platform Terminal Transmitter (PTT) (Telonics, Mesa, AZ; model ST-5) was attached to a 2 m^3 tetroon and launched in a manner similar to that of the tetroons with attached Intellisondes. A 10.5-VDC lithium battery pack supplied power to the PTT which drew a maximum of 750 ma during transmission and operated on a frequency of 401.650 MHz. A thermistor attached to the PTT measured air temperatures from - 3 to 42°C with an accuracy of 0.15°C. Geographic positions are accurate within 1 km. Each PTT transmitted tracking information and air temperature data at 90 s intervals, and data were received whenever the Argos polar-orbiting satellites ascended above the horizon with respect to the PTT. During the field projects, no PTT transmissions were received by the Argos system from 23:00 h to 04:00 h owing to the orbits of the Argos satellites. Service Argos, Inc. (Landover, MD) acquired and processed data from an Argos satellite, and transmitted files containing PTT position and temperature data every 2–4 h via the INTERNET to an IBM mainframe computer system at Texas A&M University, College Station, Texas. The data files were downloaded to a PC for analysis.

Two satellites simultaneously in polar orbit at 850 km altitude comprise the space segment of the Argos system. Instrumentation onboard the satellites receives and records data sent from the transponder, and sends data and location information to ground stations. Satellite tracking continued until the transponder signal was no longer detectable or until the transponder was forced to the ground.

2.6. Tetroon tracking schedule

Tetroons were launched from the Weslaco airport on nine nights between 11 and 23 June and tracked by vehicle using the signal from at least three Loran radio towers until the tetroon transponder radio signal was lost or until dawn, whichever occurred first. Additionally, three tetroons were released at Weslaco and tracked by the Argos system.

One successive-night tetroon tracking event was initiated from Eagle Lake, Texas, on 6–8 July. Each night the tetroon was released near sunset and tracked with a radio-equipped van for approximately 9 h. A tetroon was released the following night near the point where the previous tetroon was deflated or, in the event that the track was lost the previous night, at the estimated location of the tetroon after a 9 h flight. A second crew followed the radio-equipped van, and stopped periodically to measure vertical profiles of wind speed and direction using pibal releases. Three pibals with attached atmospheric transponders were released each night at approximately 21:00

h, 01:00 h and 07:00 h. At least two pibals without transponders were released between 21:00 h and 07:00 h.

2.7. NWS forecast trajectories

NWS forecast three-dimensional trajectories were compared with tetroon trajectories. NWS trajectories were forecast at 07:00 h prior to the nightly launch of tetroons. NWS trajectories from 19:00 h to 07:00 h were plotted to represent the forecasted nocturnal atmospheric transport. The displacement and heading of the 12 h vector-averaged NWS trajectories were prorated to 9 h for a more representative comparison with the tetroon trajectories.

3. Results

3.1. Insect emergence

The emergence dates of adult corn earworm from pupae in commercial corn fields near the tetroon release sites determined the deployment schedule of tetroons. Emergence occurred in the LRGV from 12 to 18 June with peak emergence on 17 June. Emergence at Uvalde, TX occurred from 28 June to 4 July and peaked on 2 July. The peak emergence dates in the LRGV were about one week later than normal largely due to later planting dates created by unusually heavy winter rainfall. Emergence at Wharton occurred from 26 June to 2 July with peak emergence on 30 June. Populations were much lower than normal in the LRGV and Wharton, about 0.4 pupae m^{-2} compared with 3.0 pupae m^{-2}. At Uvalde the pupal densities were near normal at about 3.0 pupae m^{-2}.

3.2. Radar

The time of insect flight initiation observed by GBR1 from 11 to 16 June indicated that tetroons would be launched from Weslaco at 21:00 h. GBR1 measured a layer of maximum insect concentration between 408 and 770 m a.g.l. from 21:12 h to 23:41 h on 14 June. Furthermore, GBR1 detected layers of maximum insect concentration between 633 and 770 m a.g.l. from 22:56 h to 23:46 h on 15 June, and intermittently at 513–770 m a.g.l. from 21:32 h to 23:29 h on 16 June. The VPR noted over-flights of insects on the nights of 14–16 June at Moore Air Field, Texas about 55 km downwind of the major source area. The peak number of insects passing over the VPR occurred at 00:00 h (3.5 h after sunset) at 244–274 m a.g.l. on 14 June. The VPR recorded similar peaks at 457 m a.g.l. at 23:00 h and from 21:00 h to 00:00 h on 15 June and 16 June, respectively.

3.3. Tetroon trajectories

Although several tetroons were launched in the LRGV between 11 and 15 June, they could not be tracked for more than about 2 h. However, the displacement speed

Table 1
Identification, transponder type, date, time, and site of tetroon releases with flight duration, displacement vectors and tetroon equilibrium levels in June and July 1992

ID	Transponder	Launch			Duration of Flight (h:min)	Displacement		Equilibrium level			
		Date	Time (h CDST)	Site		Dist. (km)	Dir. (deg)	Alt (m)	P (kPa)	T (°C)	RH (%)
T92A	LORAN	6/11	2133	WESLACO, TX	–	–	–	–	–	–	–
T92B	LORAN	6/11	2245	WESLACO, TX	1:15	24	317	358	–	–	–
T92C	LORAN	6/12	2134	WESLACO, TX	2:14	91	329	181	–	–	–
T92D	LORAN	6/13	2100	WESLACO, TX	2:32	84	324	137	–	–	–
T92E	LORAN	6/14	2107	WESLACO, TX	2:06	101	338	525	951	26.2	86
T92F	LORAN	6/15	2119	WESLACO, TX	1:11	45	321	82	–	–	–
T92G	PTT	6/16	2114	WESLACO, TX	9:00	379	338	929	887	23.1	52
T92H	LORAN	6/16	2117	WESLACO, TX	9:00	369	343	1436	860	21.2	55
T92I	PTT	6/18	2101	WESLACO, TX	9:00	310	329	923	910	23.8	60
T92J	LORAN	6/18	2116	WESLACO, TX	2:57	108	218	288	–	–	–
T92K	PTT	6/19	2100	WESLACO, TX	9:00	134	349	1041	900	20.2	65
T92L	LORAN	6/19	2118	WESLACO, TX	9:00	358	340	869	916	24.0	54
T92M	LORAN	6/22	2124	WESLACO, TX	9:00	246	335	895	917	23.9	61
T92N	–	6/23	2202	COTULLA, TX	38:58	1009	16	500	–	–	–
T92O	LORAN	7/6	2128	EAGLE LAKE, TX	8:59	466	30	786	927	25.9	23
T92P	LORAN	7/7	2124	ATLANTA, TX	9:00	566	47	851	925	24.9	68
T92Q	LORAN	7/8	2218	JONESBORO, AR	9:00	362	79	728	939	24.4	73

Displacement distance and direction are resultant values. T and RH values for T92H are estimated from pressure values. Altitude values are referenced to the launch site elevation.

and direction on those nights was similar to that of tetroons launched after 15 June and tracked all night. Details of the tetroon trajectories for all launches are summarized in Table 1. Identification labels have been assigned to the tetroon launches. Six tetroons were tracked successfully all night from Weslaco, and one was tracked all night from Eagle Lake, Texas (near Wharton). An additional tetroon (T92N) was released at Cotulla, Texas, from the endpoint of T92M. This tetroon was not equipped with a transponder, but it was recovered at LeFlore, Oklahoma.

Tetroon T92G was launched from the Weslaco airport at 21:14 h on 16 June (Fig. 1). The tetroon was ballasted for an initial equilibrium level of 929 m a.g.l., and was tracked via the Argos satellite. Data showed an initial displacement toward 338° at 11.7 m s^{-1} with a subsequent acceleration to 12.8 m s^{-1} at 357°. After 9 h the tetroon was located 20 km west-northwest of Hondo, Texas. Tetroon T92H was launched simultaneously with T92G but was ballasted for an initial equilibrium level of 1436 m a.g.l. T92H was tracked via ground vehicle to near Hondo after a 9 h displacement and moved at a velocity of 10.5 m s^{-1} toward 315° for 2.8 h then accelerated to 13.3 m s^{-1} toward 354°. The veering tendency of the wind direction at the 92.5 kPa geopotential-height at Brownsville, Del Rio, and Corpus Christi, Texas at 19:00 h on 16 June and 07:00 h on 17 June approximated the trajectory of T92G which was ballasted to drift at about that altitude. The trajectory of T92G and the winds at the 92.5 kPa geopotential-height maintained a north-northwestward direction. However, the trajectory of T92H, which was ballasted for a geopotential-height of about 86.0 kPa, veered from a north-northwestward to a northward displacement. Surface

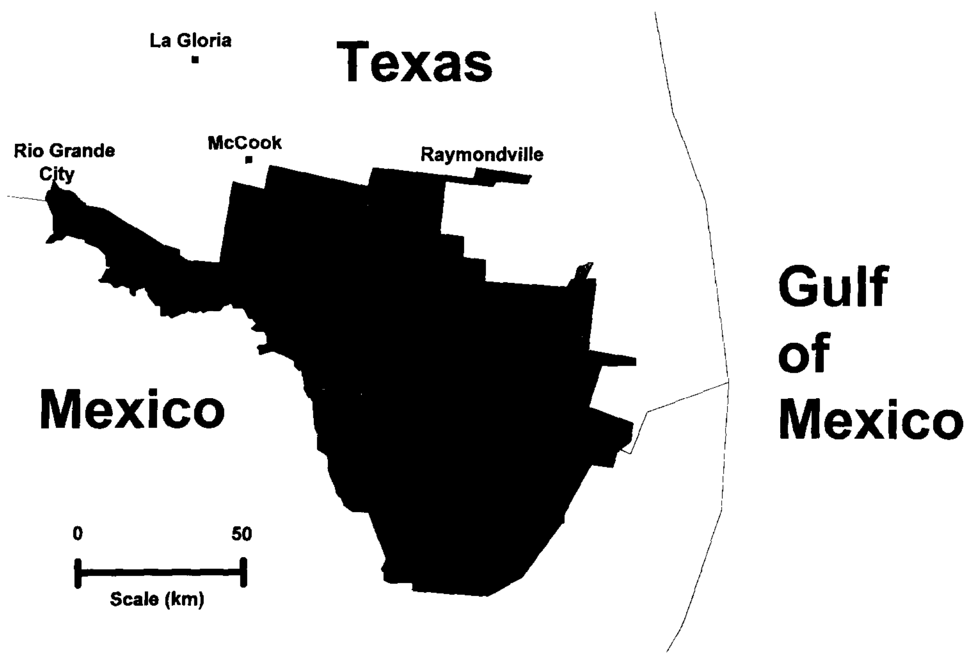

Fig. 1. Irrigated agricultural land in the Lower Rio Grande Valley (LRGV) of Mexico and the US.

synoptic weather conditions following the track of T92G and T92H (07:00 h on 17 June) showed a cold front extending across central Oklahoma to El Paso, Texas, and a trough of low pressure extending southward from the front through the Big Bend area of Texas (National Oceanic and Atmospheric Administration (NOAA), 1992).

Tetroon T92I was launched on 18 June at Weslaco at 21:01 h (Fig. 2). The tetroon drifted toward 326° at 8.5 m s^{-1} and was located about 40 km south of Uvalde, Texas,

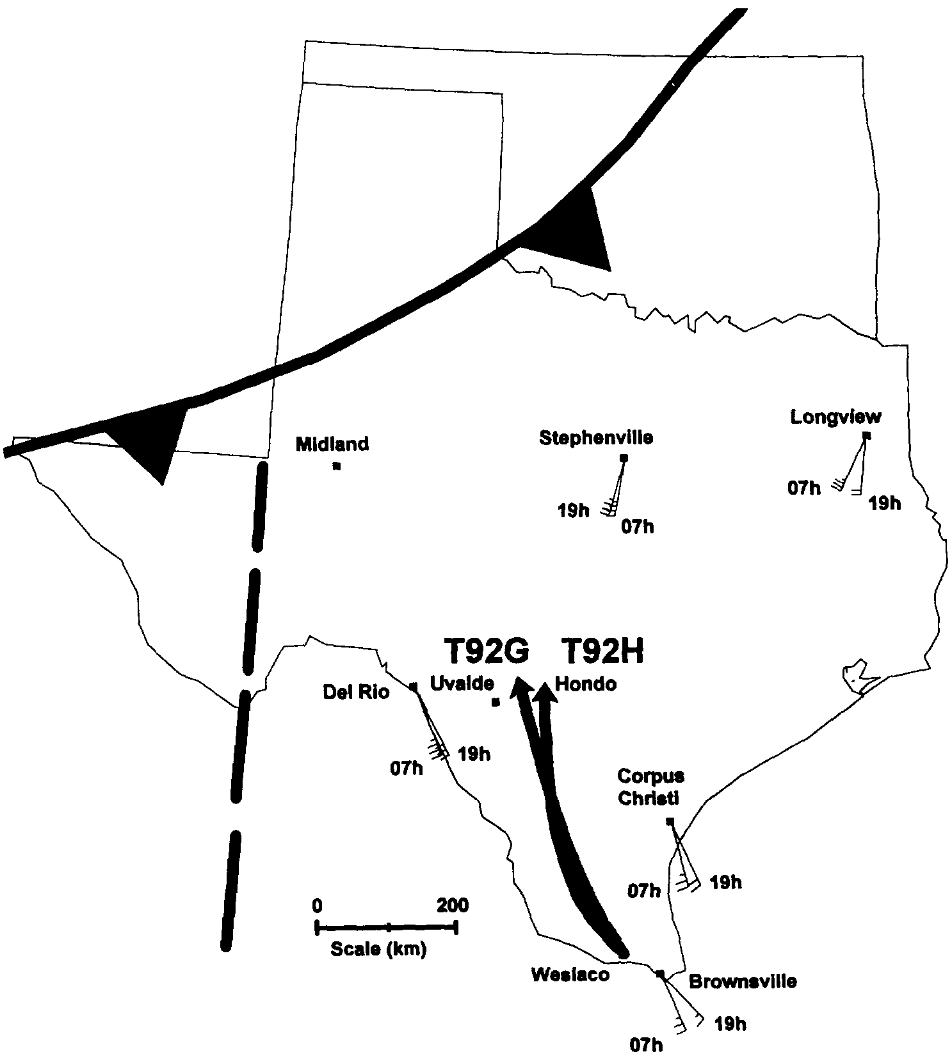

Fig. 2. Nine hour nocturnal boundary layer trajectories of tetroons launched at approximately 21:15 h from Weslaco, Texas, on 16 June 1992. T92G was ballasted to drift at 929 m a.g.l., and was tracked by the Argos satellite. Tetroon T92H was ballasted to drift at 1436 m a.g.l., and was tracked by radio-equipped vehicle. Wind velocity flags for 19:00 h on 16 June and 07:00 h on 17 June are shown for NWS rawinsonde locations.

at 06:01 h. Wind at the 92.5 kPa geopotential-height veered from 19:00 h on 18 June to 07:00 h on 19 June at Brownsville, Del Rio, and Corpus Christi. Although T92I drifted at this altitude, its trajectory showed no significant curvature except slight backing during the final 20% of its displacement. The vector-average of the NWS forecast three-dimensional trajectories at the surface and 85.0 kPa

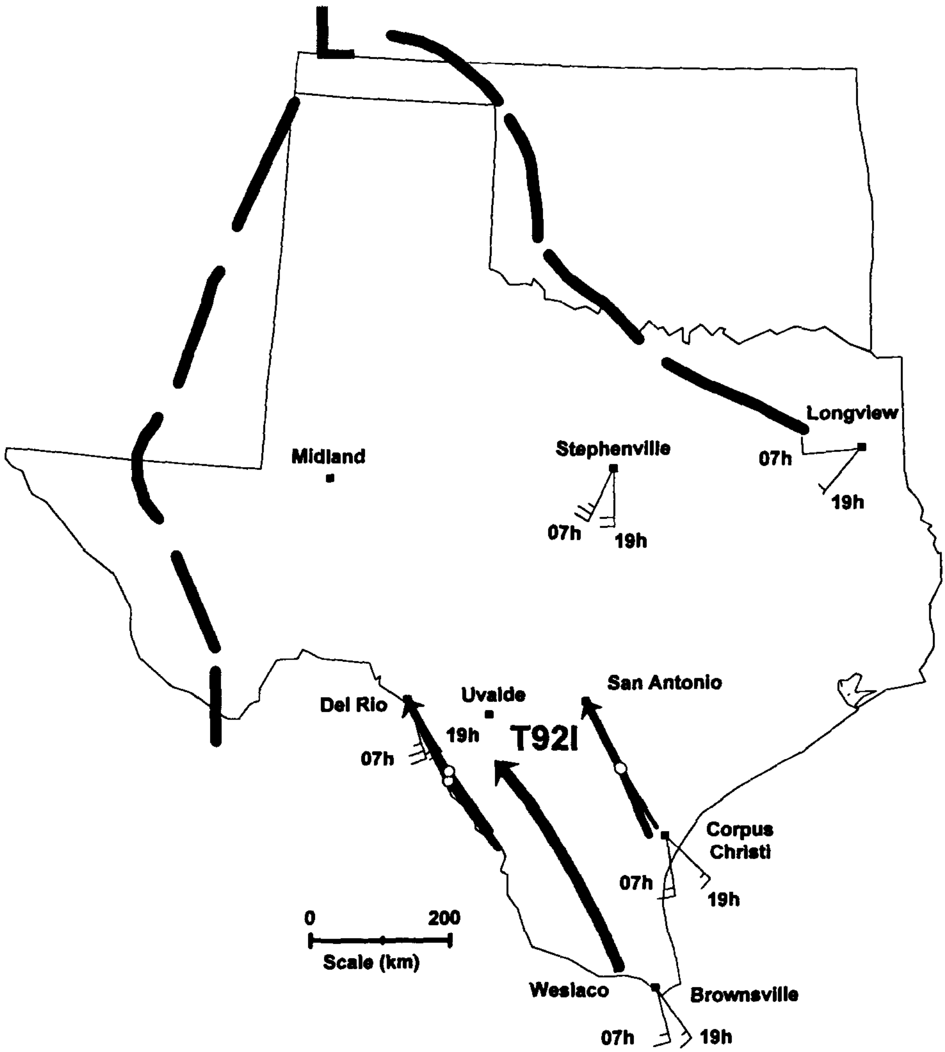

Fig. 3. Nine hour nocturnal boundary layer trajectory of a tetroon launched at 21:01 h from Weslaco, Texas, on 18 June 1992. T92I was ballasted to drift at 923 m a.g.l., and was tracked by the Argos satellite. Wind velocity flags for 19:00 h on 18 June and 07:00 h on 19 June are shown for NWS rawinsonde locations. Twelve hour NWS forecast trajectories terminating at the surface (thin arrow) and 85.0 kPa geopotential-height (medium arrow) at 07:00 h on 19 June, are shown where the open circles indicate the forecast locations at 01:00 h on 19 June.

geopotential-height terminating at Del Rio and San Antonio showed an equal displacement heading, but when prorated to a 9 h displacement was only 53% as long as the trajectory of T92I. Surface synoptic weather conditions at 07:00 h on 19 June showed a low pressure system over southeastern Colorado, with a (NOAA, 1992) trough of low pressure extending southward through the Big Bend area and another southeastward to Longview, Texas.

Tetroon T92L was ballasted for an initial equilibrium level of 869 m a.g.l. and released at 21:18 h on 19 June at Weslaco (Fig. 3). Tetroon T92K was ballasted for an

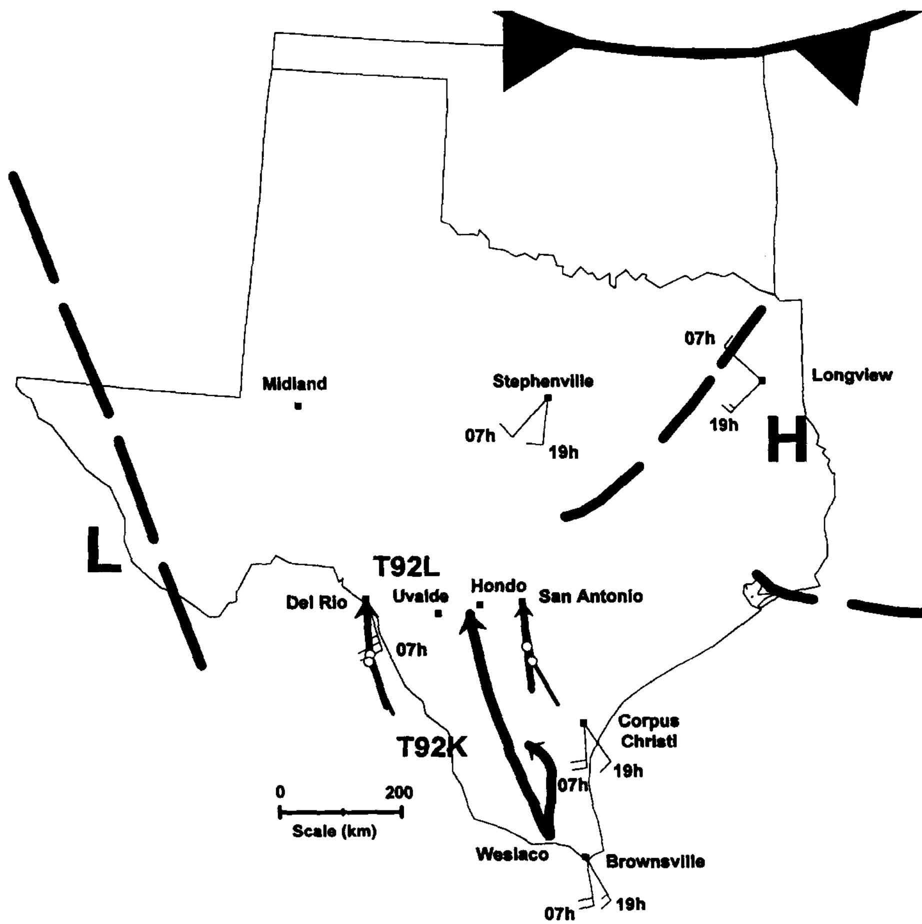

Fig. 4. Nine hour nocturnal boundary layer trajectories of tetroons launched at approximately 21:10 h from Weslaco, Texas, on 19 June 1992. T92K was ballasted to drift at 1041 m a.g.l., and was tracked by the Argos satellite. Tetroon T92L was ballasted to drift at 869 m a.g.l., and was tracked by radio-equipped vehicle. Wind velocity flags for 19:00 h on 19 June and 07:00 h on 20 June are shown for NWS rawinsonde locations. Twelve hour NWS forecast trajectories terminating at the surface (thin arrow) and 85.0 kPa geopotential-height (medium arrow) at 07:00 h on 20 June, are shown where the open circles indicate the forecast locations at 01:00 h.

initial equilibrium level of 1041 m a.g.l. and released at 21:00 h (Fig. 3). The Argos satellite tracked T92K northward at 4.3 m s^{-1} to a location 80 km west-southwest of Corpus Christi after 9 h. The initial velocity of T92L was 10.8 m s^{-1} toward 336° but subsequently changed to 11.8 m s^{-1} at 345°. The tetroon was tracked for 9 h to 20 km west-southwest of Hondo. Surface synoptic weather conditions at 07:00 h on 20 June showed a cold front along the northern border of Oklahoma, one trough of low pressure from central New Mexico to the Big Bend area and another from central Texas to Longview (NOAA, 1992). Winds at the 92.5 kPa geopotential-height veered from 19:00 h on 19 June to 07:00 h on 20 June at Brownsville and Corpus Christi, but

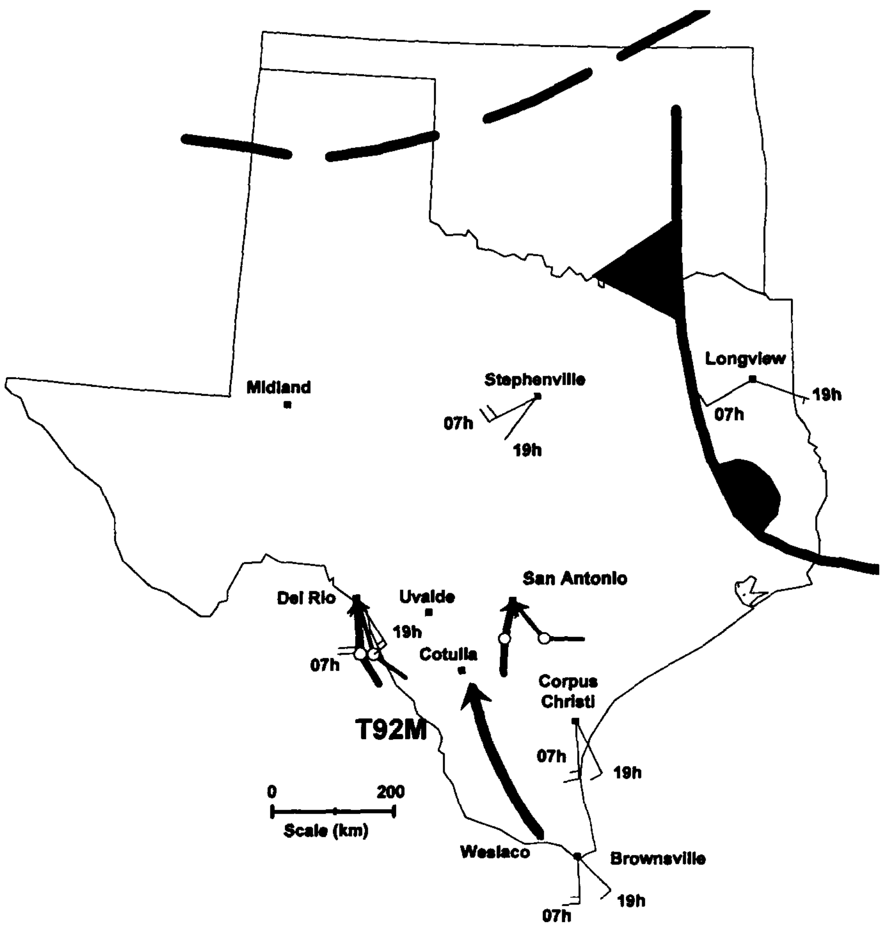

Fig. 5. Nine hour nocturnal boundary layer trajectories of a tetroon launched from Weslaco, Texas at 21:24 h on 22 June 1992. T92M was ballasted to drift at 895 m a.g.l., and was tracked by radio-equipped vehicle. Wind velocity flags for 19:00 h on 22 June and 07:00 h on 23 June are shown for NWS rawinsonde locations. Twelve hour NWS forecast trajectories terminating at the surface (thin arrow) and 85.0 kPa geopotential-height (medium arrow) at 07:00 h on 23 June are shown, where the open circles indicate the forecast locations at 01:00 h.

no data were available for Del Rio at 07:00 h on 21 June. The prorated (9 h) vector-average of the NWS forecast three-dimensional trajectories at the surface and 85.0 kPa geopotential-height at Del Rio and San Antonio were 36% as long as, and 5° clockwise to, the trajectory of T92L. The same prorated vector-average of the NWS forecast three-dimensional trajectories was 97% as long as trajectory T92K, and 5° counterclockwise to the trajectory of T92K.

Tetroon T92M was launched from Weslaco at 21:24 h on 22 June (Fig. 4). The tetroon drifted at an initial equilibrium level of 895 m a.g.l. at 6.2 m s^{-1} toward 332° for 4.5 h, then accelerated to 7.8 m s^{-1} toward 341°. The tracking crew tracked the tetroon for 9 h and observed it drifting over Cotulla, Texas, at 06:24 h on 23 June. A vertical atmospheric profile at 07:00 h documented a wind velocity of 7.6 m s^{-1} toward 350° at 750 m a.g.l., where the tetroon was drifting 350 m above the maximum wind speed level (12.0 m s^{-1} toward 5°). The veering of the trajectory of T92M was documented by the wind at the 92.5 kPa geopotential-height at 19:00 h on 23 June and 07:00 h on 24 June at Del Rio, Brownsville, and Corpus Christi. The prorated 9 h vector-average of the NWS forecast trajectories at the surface and 85.0 kPa geopotential-height at Del Rio and San Antonio were 43% as long as the trajectory of T92M, and 5° clockwise to the trajectory of T92M.

3.4. Vertical displacements of tetroons

Vertical displacements of four vehicle-tracked tetroons (T92E, T92H, T92L, and T92M) are shown in Fig. 5. In each case, standard deviation values of the vertical displacements are less than 21 m (Table 2). Mechanical turbulence induced by wind shear or surface roughness was not strongly evident in these data. The trajectory altitudes did not appear to follow the terrain. However, the altitude of T92L increased markedly during the last 25 km of flight over the higher terrain near Hondo.

Table 2
Atmospheric characteristics of equilibrium flight levels of drifting tetroons in south-central Texas from 14 to 22 June 1992, and in the central US from 6 to 8 July 1992

Variable	Mean/SD	14 June	16 June	19 June	22 June	6 July	7 July	8 July
Number of observations		1071	13682	13038	13638	10871	1893	2717
Elapsed Time (h)		1.09	8.49	8.60	8.58	8.16	2.82	3.56
Altitude	Mean	568	1436	869	895	759	851	728
(m a.g.l.)	SD	9.9	20.6	20.5	12.5	10.9	8.0	19.7
Barom. pressure	Mean	94.7	86.0	91.6	91.7	92.7	92.5	93.9
(kPa)	SD	0.1	0.2	0.2	0.1	0.1	0.1	0.2
Air temp.	Mean	26.1	21.2	24.0	23.9	25.9	24.9	24.4
(°C)	SD	0.0	1.0	0.6	0.5	0.4	0.2	0.3
RH (%)	Mean	86.5	55.0	54.4	60.8	23.1	68.4	72.8
	SD	0.1	7.0	1.7	6.4	1.1	0.8	4.5

3.5. Successive-night tetroon trajectories

The first (T92O) of the three successive-night tetroon releases originated from Eagle Lake on 6 July (Fig. 6). T92O was ballasted for an initial equilibrium level of 786 m a.g.l. and released at 21:28 h. The tetroon was tracked by vehicle for 466 km over 9 h. The tetroon was deflated near McLeod, Texas, and landed in a densely forested bayou and was not recovered. The prorated 9 h vector-average of the NWS forecast trajectories at the surface and 85.0 kPa geopotential-height at Shreveport, Louisiana was 56% as long as the trajectory of T92O, and 15° counterclockwise to trajectory T920. Synoptic weather conditions at 07:00 h on 7 July indicated a stationary front extending from western Tennessee through Atlanta, Georgia, and a trough of low pressure across the northwestern corner of the Texas Panhandle (NOAA, 1992).

The second (T92P) tetroon was ballasted for an initial equilibrium level of 851 m a.g.l. and released near Atlanta, Texas (15 km northwest of McLeod), at 21:24 h on 7 July (Fig. 7). The tetroon was tracked northward by vehicle toward the Ozark National Park; however, the trajectory subsequently accelerated and veered

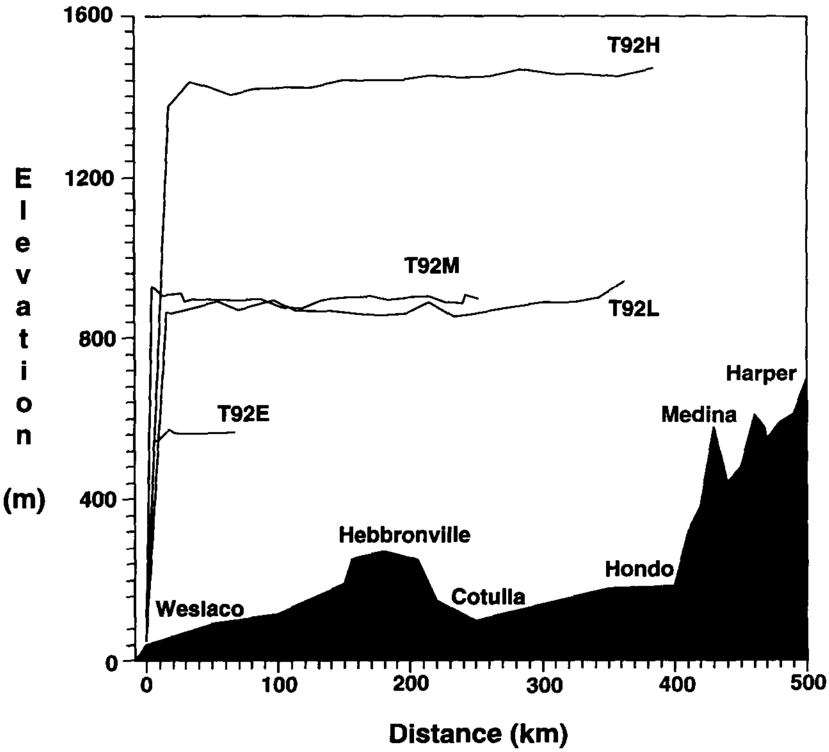

Fig. 6. Vertical displacements of vehicle-tracked tetroons launched from Weslaco, Texas at about 0.5 h after sunset on 14 June (T92E), 16 June (T92H), 19 June (T92L), and 22 June 1992 (T92M). The approximate elevation of the underlying terrain is noted by a bold solid line.

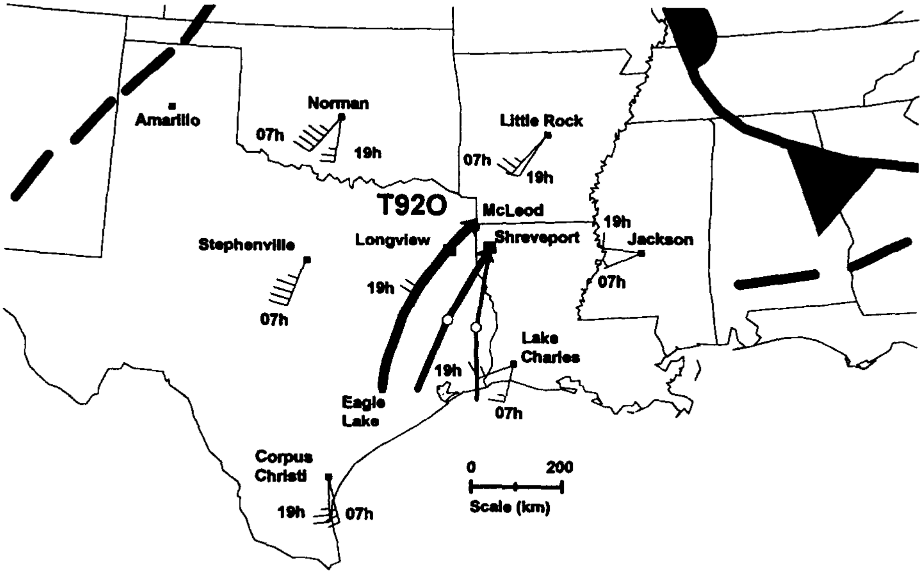

Fig. 7. Nine hour nocturnal boundary layer trajectory of tetroon T92O launched at 21:28 h on 6 July 1992 from Eagle Lake, Texas. The solid triangle denotes the observed trajectory endpoint. Wind velocity flags for 19:00 h on 6 July and 07:00 h on 7 July are shown for NWS rawinsonde locations. Twelve hour NWS forecast trajectories terminating at the surface (thin arrow) and 85.0 kPa geopotential-height (medium arrow) at 07:00 h on 7 July are shown, where the open circles indicate the forecast locations at 01:00 h.

northeastward toward Jonesboro, Arkansas. The tracking van lost telemetry from the transponder at 00:58 h on 8 July near Hot Springs, Arkansas. Furthermore, the two crews could not communicate effectively while driving through the southern foothills of the Ozark National Park. The two crews rendezvoused at Little Rock, Arkansas, and continued to pursue the tetroon based on a trajectory estimated from vertical atmospheric profiles. The estimated trajectory indicated that the tetroon should have deflated after the 9 h flight about 50 km northwest of Jonesboro. Thundershowers were active near Jonesboro at 05:30 h on 8 July and the tetroon was eventually discovered 136 km downwind near New Madrid, Missouri, on 10 July. The prorated 9 h vector-average of the NWS forecast trajectories at the surface and 85.0 kPa geopotential-height at Memphis, Tennessee was 50% as long as the trajectory of T92P, and 10° counterclockwise to trajectory T92P. Synoptic weather conditions at 07:00 h on 8 July showed a cold front extending through central Kansas to the Texas Panhandle and a warm front from central Illinois to South Carolina (NOAA, 1992).

The third (T92Q) release was made at 22:18 h on 8 July at Jonesboro where we estimated that T92P had deflated that morning at 06:24 h (Fig. 8). The tetroon drifted initially at an altitude of 728 m a.g.l. toward 70° then moved eastward toward Mayfield, Kentucky. Telemetry was lost near Mayfield at 00:17 h on 9 July. Telecommunications between vehicles had again failed while passing through the hilly terrain of western Kentucky. However, the two crews independently pursued the tetroon incommunicado, until they re-established contact at 05:08 h near Nashville,

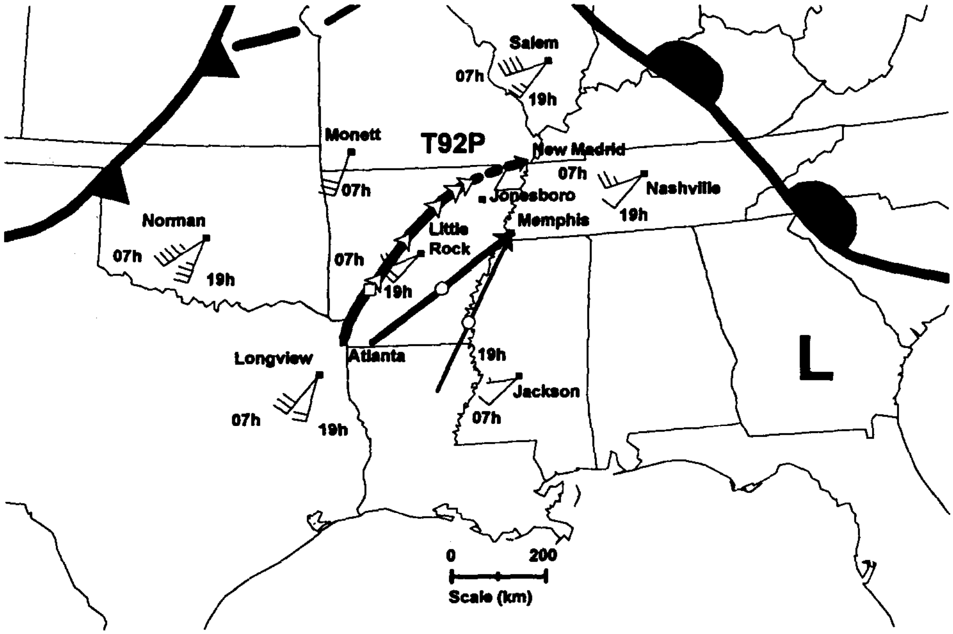

Fig. 8. Nine hour boundary layer trajectory of tetroon T92P launched at 21:24 h on 7 July 1992 from Atlanta, Texas. An empty square denotes location at which radio-tracking was aborted, empty triangles denote trajectory points estimated from nearby atmospheric soundings, and solid triangles denote observed trajectory endpoints. Wind velocity flags for 19:00 h on 7 July and 07:00 h on 8 July are shown for NWS rawinsonde locations. Twelve hour NWS forecast trajectories terminating at the surface (thin arrow) and 85.0 kPa geopotential-height (medium arrow) at 07:00 h on 8 July are shown, where the empty circles indicate the forecast locations at 01:00 h.

TN. They had independently estimated that the tetroon would pass near Nashville at 06:18 h. The estimated trajectory endpoint (30 km north of Nashville) was based on vertical atmospheric profiles along the approximate trajectory. The prorated 9 h vector-average of the NWS forecast trajectories at the surface and 85.0 kPa geopotential-height at Nashville was 65% as long as trajectory T92Q and 3° counterclockwise to the trajectory of T92Q. A cold front extended across northern Kansas through central Illinois at 07:00 h on 9 July (NOAA, 1992) (Fig. 9).

4. Conclusions

Instrumented tetroons have been successfully deployed to monitor nocturnal atmospheric transport conditions during periods of peak emergence of corn earworm moths. The tetroon trajectories presented here should be more representative of the distance and direction of corn earworm moth flights than are the NWS trajectory forecasts because they are measured nearer to the altitude and during the time of migratory insect flights. The combination of tetroon trajectories with radar

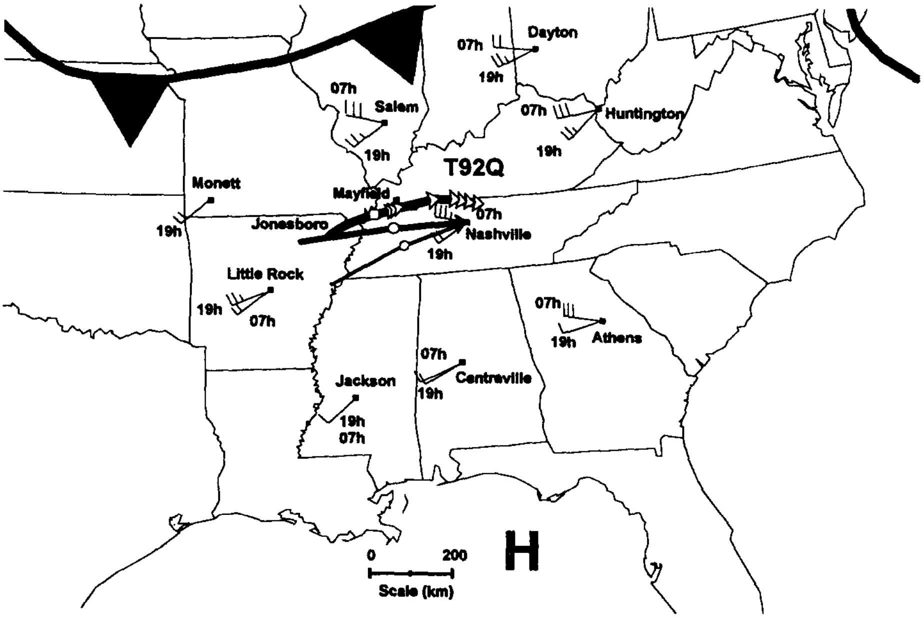

Fig. 9. Nine hour nocturnal boundary layer trajectory of tetroon T92Q launched at 22:18 h on 8 July 1992 from Jonesboro, Arkansas. An empty square denotes location at which radio-tracking was aborted, empty triangles denote trajectory points estimated from nearby atmospheric soundings, and solid triangles denote observed trajectory endpoints. Wind velocity flags for 19:00 h on 8 July and 07:00 h on 9 July are shown for NWS rawinsonde locations. Twelve hour NWS forecast trajectories terminating at the surface (thin arrow) and 85.0 kPa geopotential-height (medium arrow) at 07:00 h on 9 July are shown, where the empty circles indicate the forecast locations at 01:00 h.

entomological measurements should be able to discriminate insect flight behaviors and abiotic mechanisms and cues affecting the initiation, dispersal, and termination of long-distance insect flights. We conclude from these tetroon trajectories that atmospheric transport conditions are present at the altitudes of flight migrating corn earworms adults to aid in their displacements of several hundred kilometers from emergence sites in southern Texas. Furthermore, they can readily travel more than 1400 km if they fly for three successive nights from southeastern Texas. These findings support recent results from backtrack analysis of migratory corn-earworms using specific pollen markers (Lingren et al., 1994). We believe that the tetroon trajectories presented here will aid in the development of plans for monitoring and managing migratory insects over wide areas.

NWS trajectory forecasts accurately estimated the tracks of tetroon drifting from Eagle Lake, Texas to Nashville, Tennessee in 3 nights, but estimated distances that were only about 60% as long as tetroon trajectories from Weslaco, Texas. The low accuracy in estimating nocturnal tetroon trajectories from Weslaco was due to the development of a nocturnal wind jet that frequently develops in south-central Texas at about 600 m a.g.l. Atmospheric data at 92.5 kPa (approximately 750 m m.s.l. (above mean sea level)) have been reported by NWS soundings since February 1991, and should be considered as inputs to new NWS trajectory forecasts of the boundary layer flow.

Several limitations to the present vehicular tracking system were identified during our study and adjustments are suggested that may enhance field operations as follows:

(1) installation of direction-finding radio systems in each of the radar units would allow radar operators to more accurately adjust their position with respect to the drifting tetroon and circumvent telecommunication problems that occurred in remote areas with limited telecommunications coverage;

(2) remote control of the density of a drifting tetroon would allow the equilibrium level to more accurately represent the dynamic altitude of greatest flight concentration during insect ascent or descent, and would force the tetroon to the ground on demand, increasing safety and efficient use of personnel, and providing for immediate tetroon recovery.

Future tetroon tracking and coincident radar entomological measurements should attempt to: (1) further determine behavioral contributions to the vertical displacement of migrating insects; (2) determine behavioral contributions to long-distance insect dispersal; (3) modify predictive models of long-distance insect dispersal. Field measurements should address data requirements for nocturnal insect migration models not satisfied spatially and temporally by the existing National Weather Service observation networks. The measurements should reveal the component of active insect flight speed, insect orientation, vertical movement of insects, and insect fall-out. Collectively, these insect flight behaviors and their degree of dependence on atmospheric variables will contribute significantly to improved accuracy of predictive insect migration models. Furthermore, mark-recapture studies should be conducted concurrently to validate the insect dispersal models.

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